Evaluation of two dental registration-splint techniques for surgical navigation in cranio-maxillofacial surgery

Venosta, Dominik ; Sun, Yi ; Matthews, Felix ; Kruse, Astrid L ; Lanzer, Martin ; Gander, Thomas ; Grätz, Klaus W ; Lübbers, Heinz-Theo

Abstract: BACKGROUND: Surgical navigation requires precise registration of the pre-operative image dataset to the patient in the operation theatre. Different marker-based and marker-free registration techniques are available, each of them with advantages and disadvantages regarding precision and clinical handling. In this model study, the precision of two dental splint techniques for marker-based registration is analyzed. MATERIALS AND METHODS: A synthetic full-size human skull was registered with its cone beam computed tomography dataset using (a) a dentally-mounted "rapid" occlusal splint with five titanium screws directly attached to the splint, (b) an "extender", a dentally-mounted occlusal splint with similar fiducials fixed to an extension of the splint. The target registration error was measured for 170 landmarks distributed over the viscero- and neurocranium in 10 repeats per splint type using the Vector Vision(2) (BrainLAB AG, Heimstetten, Germany) navigation system. Statistical and graphical evaluations were performed per anatomical region. RESULTS: In the periorbital region, the rapid splint, with an average deviation of 1.50 mm (SD = 0.439) showed greater accuracy than the extender with 1.76 mm (SD = 0.525). The viscerocranial results for both splints were similar (extender 1.84 mm, SD = 0.559, rapid occlusal splint 1.86 mm, SD = 0.686). In the cranial vault region, registration with the extender (2.33 mm, SD = 0.685) proved to be more precise than with the rapid splint (2.86 mm, SD = 0.929). CONCLUSIONS: Due to the more compact dimension of the rapid occlusal splint, errors close to the splint were smaller compared to the extender technique. The advantage of greater distances between the registration fiducials on the extender is particularly important in areas such as the orbital roof, the cranial vault, and the lateral skull base.

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ABSTRACT

Background

Surgical navigation requires precise registration of the preoperative image dataset to the patient in the operation theatre. Different marker-based and marker-free registration techniques are available, each of them with advantages and disadvantages regarding precision and clinical handling. In this model study, the precision of two dental splint techniques for marker-based registration is analyzed.

Materials and methods

A synthetic full-size human skull was registered with its cone beam computed tomography dataset using (a) a dentally mounted “rapid” occlusal splint with five titanium screws directly attached to the splint, (b) an “extender”, a dentally-mounted occlusal splint with similar fiducials fixed to an extension of the splint. The target registration error was measured for 170 landmarks distributed over the viscero- and neurocranium in 10 repeats per splint type using the Vector Vision^2 (BrainLAB AG, Heimstetten, Germany) navigation system. Statistical and graphical evaluations were performed per anatomical region.

Results

In the periorbital region, the rapid splint with an average deviation of 1.50mm (SD=0.439) showed greater accuracy than the extender with 1.76mm (SD=0.525). The viscerocranial results for both splints were similar (extender 1.84mm, SD=0.559, rapid occlusal splint 1.86mm, SD=0.686). In the cranial vault region, registration with the extender (2.33mm, SD=0.685) proved to be more precise than with the rapid splint (2.86mm, SD=0.929).

Conclusions

Due to the more compact dimension of the rapid occlusal splint, errors close to the splint were smaller compared to the extender technique. The advantage of greater distances between the registration fiducials on the extender is particularly important in areas such as the orbital roof, the cranial vault, and the lateral skull base.

INTRODUCTION

The complex three-dimensional (3D) geometry and the requirement of precise symmetrical reconstruction are major challenges for reconstructive maxillofacial surgery. Pre-operative planning with a rapid prototype based on a multi-detector computer tomography (MDCT) scan or on a cone beam CT (CBCT) is a time-consuming and costly approach.(*Hassfeld and Muhling,* 1998) Even if the exact planning based on a patient specific model offers many advantages, it often fails to precisely transfer the planning to the complex craniofacial anatomy. Computer-assisted surgical navigation can be of help for pre-operative planning based upon different radiological datasets and has become a common method in craniofacial surgery.(*Hassfeld et al.,* 2000; *Yeshwant et al.,* 2005a; *Yeshwant et al.,* 2005b; *Ritter et al.,* 2006; *Luebbers et al.,* 2008) The most important aspect for technically precise intra-operative navigation is the correct registration of the image dataset of the patient.(*Marmulla and Niederdellmann,* 1998; *Marmulla,* 1999; *Luebbers et al.,* 2008) The exact registration has a direct bearing on the accuracy of all subsequent navigation tasks.(*Eggers et al.,* 2006) The structures established pre-operatively by means of a CBCT or an MDCT are transferred to the patient during registration.(*Hassfeld and Muhling,* 2000; *Gellrich et al.,* 2002; *Schmelzeisen et al.,* 2002; *Marmulla et al.,* 2004b; *Schmelzeisen et al.,* 2004; *Hohlweg-Majert et al.,* 2005)

Registration can be subdivided into distinct groups. One differentiates between marker-based (*Altobelli et al.,* 1993; *Hassfeld et al.,* 1995; *Howard et al.,* 1995; *Schramm et al.,* 1999; *Luebbers et al.,* 2008) and marker-free (*Troitzsch et al.,* 2003; *Marmulla et al.,* 2004a; *Hoffmann et al.,* 2005; *Marmulla et al.,* 2005b) registration techniques. In the case of marker-based registration, the markers have to be in the patient prior to the establishment of the dataset in an inter-operatively solid and accessible position. For instance, the markers may be titanium screws(*Sinikovic et al.,* 2007; *Luebbers et al.,* 2008; *Lubbers et al.,* 2011c) placed at clear, easily detectable bone structures during surgery.

In addition, markers may be fitted on a splint fixed to the maxillary teeth (*Schramm et al.,* 2001) or self-adhesive markers may be glued to the skin.(*Alp et al.,* 1998; *Hardy et al.,* 2006)

In the case of marker-free point-to-point registration, easily detectable, marked anatomical structures (*Swennen et al.,* 2006; *Lubbers et al.,* 2010; *Lubbers et al.,* 2011b; *Sun et al.,* 2012) that must also be discernible on the sectional views of the dataset are used. Another marker-free registration is laser surface scanning, which matches random points on the skin surface to the soft tissue data of the radiological dataset.(*Grevers et al.,* 2002; *Marmulla et al.,* 2004a; *Marmulla et al.,* 2004b; *Hoffmann et al.,* 2005; *Marmulla et al.,* 2005a; *Marmulla et al.,* 2005b) For technical reasons, the data obtained by cone beam CT is relatively unsuitable for this surface matching technique.

However, each of these registration methods is subject to error. The present study compares (*van den Elsen et al.,* 1982; *Maciunas et al.,* 1994) the registration methods of two different splints (a “rapid” occlusal splint, Fig. 1, and an extender, Fig. 2). The accuracy of measurement is separately assessed for three anatomical regions (orbital, maxillary, and cranial). Earlier studies have already dealt with this topic. (*Luebbers et al.,* 2008; *Bettschart et al.,* 2011) They showed that using additional titanium screws directly attached to the skull can optimize the registration via splints. The present study intends to evaluate possible optimization when a purely splint-based registration is utilized. In addition the “rapid” occlusal splint, which offers decisive clinical advantages, is evaluated.

MATERIALS AND METHODS

Ten series of measurements were taken in vitro on a synthetic human skull model (A20, 3B Scientific, Hamburg, Germany) using the optical navigation system Vector Vision^2 (Brainlab AG, Feldkirchen, Germany).

Splint preparation

For the rapid occlusal splint (a) a prefabricated splint that carried the necessary fiducials for point-to-point registration was individualized with impression material directly on the skull model. The splint was than removed from the model and any interfering material was removed until precise and stable repositioning of the splint was easily possible (Figure 1). Overall, the approach was similar to clinical situations involving acute trauma patients. (*Lubbers et al.,* 2011a)

For the extender, an occlusal splint with extension, an impression was taken from the skull model. An occlusal splint was thermoformed on the plaster model. To this splint a light extension made of glass fiber-reinforced plastic was mounted, which then carried the registration fiducials. To achieve necessary stiffness, the construction was reinforced with two carbon fiber tubes (Figure 2).

Model preparation

The same synthetic human skull model that had been used in the previous survey of our group (*Luebbers et al.,* 2008; *Bettschart et al.,* 2011) was used to allow direct comparison of the measurements. The 170 drilling holes were distributed over the entire viscero- and neurocranium; each one had a diameter of 1.2mm. The skull was scanned with a high-definition CBCT (KaVo 3D eXam, Kavo Dental GmbH, Biberach/Riss, Germany). A resolution of 0.4 × 0.4 × 0.4 mm was set for the image and the skull was placed in such a way as to enable a full representation, including the splint in one dataset. The DICOM data was subsequently imported into the Brainlab iPlan ENT 2.6 (Brainlab AG, Feldkirchen, Germany) software. All of the drillings and the center of the screws/fiducials fixed to the splints were tagged as shown in figure 3. The individual landmarks, as well as the screws, were identified manually on the coronal, sagittal, and axial views as well as by 3D projection. The use of tenfold magnification ensured maximal precision. The final datasets were fed into the navigation system via a USB drive.

Image registration and surgical navigation

The navigation system was set up in a room under daylight conditions that had been partially darkened in order to avoid, as much as possible, interference from ambient light. Basically, the lighting was similar to that of a standard operating theatre. A reference star was fixed to the skull in a typical clinical parietal position off the midline. Every serial measurement included the registration and the subsequent measuring of the 170 landmarks. In both splints, registration was done point-to-point directly via the screws (titanium bone screw, Modus 1.5 x 6mm, Medartis AG, Basel, Switzerland), which in case of the rapid occlusal splint, (a) were fixed to the splint in case of the extender (b) were fixed to the extensions of the splint. There were 10 serial measurements for every splint. All measurements and referencing were done with Vector Vision Pointer (Brainlab AG, Feldkirchen, Germany).

The spatial deviation – representing the so called target registration error - of the respective landmark is calculated as follows: $d = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$ (Δx, Δy, and Δz is the difference between the tip of the pointer in the world space and the landmark in the image space in the X, Y, and Z direction separately). The system was designed to calculate the spatial deviation to the nearest landmark. For that reason, landmarks were placed at sufficient distances from each other. In addition, all drill holes (serving as landmarks) and their corresponding labels in the software were numbered consistently; manual checks were conducted to make sure that the navigation system calculated the distance to the correct label for each measurement.

Data evaluation

Average values of the individual landmarks were determined based upon 10 serial measurements. By analogy to preliminary studies (*Luebbers et al.,* 2008; *Bettschart et al.,* 2011), the skull was divided into 3 anatomical regions: the periorbital region, viscerocranial around the periorbital region, and the neurocranium. The deviations calculated for each anatomical region were compared for both splints using descriptive statistics. The deviations of the measurements were illustrated with Matlab (Version 7.1/R14, TheMathworks Inc., Natrick, USA).

RESULTS

All drillings for the landmarks were perfectly identifiable within the iPlan®-Software on the reconstruction of the 3D skull model. When determining the landmarks, one must take into account the fact that the tip of the measuring probe is inserted between approximately 0.5mm to 1mm into the drilling hole during the measuring process. It was possible to do 10 serial measurements for each splint without any difficulty. Average, minimum, and maximum deviations, as well as standard deviations for both splints according to the three anatomical regions are presented in Table 1. In the periorbital region, the “rapid” occlusal splint with 1.50mm (SD=0.439) deviation, is slightly more precise than the measurements with the extender with a deviation of 1.76mm (SD=0.525). In the area of the viscerocranium, both the “rapid” occlusal splint (1.86mm, SD=0.686) and the extender (1.84mm, SD=0.559) exhibited more or less the same deviations. In the area of the neurocranium, i.e., with a major distance to the referencing markers, the extender proved to be much more precise. The average deviation of the extender was at 2.33mm (SD=0.685) and the deviation of the “rapid” occlusal splint was at 2.86mm (SD=0.929). Outside the mid-face area, there was a clear correlation between the deviation and the distance to the centroid of the polygon spanned by the individual referencing markers (Figure 4). The biggest deviation occurred in the temporal and occipital regions. The best representation of regional measuring accuracy of the individual registration methods was obtained in a color-coded virtual 3D model of the skull. (Figures 5 & 6)

DISCUSSION

In essence, our results correspond to the ones of existing studies (*Luebbers et al.,* 2008; *Bettschart et al.,* 2011) and underline the fact that the type and accuracy of the registration have a major influence upon the accuracy of the measurement. (*Schlaier et al.,* 2002; *Marmulla et al.,* 2004a; *Hoffmann et al.,* 2005; *Hardy et al.,* 2006) The measurement results also show increasing inaccuracy as the distance between the region of interest and the registration fiducials increases. In addition to the exact, clear positioning of the splint, additional factors also play a role in reality, which could be ignored for our synthetic human skull model. For instance, the patient needs to have a sufficient number of teeth to allow for a reliable position for the splint. The teeth also have to be firmly anchored in the parodontium; in sum, they must not move too much. In accident cases, the operative field should not be in the area of the teeth to which the splint is fixed. Should this be the case, there is the risk that it may be impossible to perform the necessary intra-operative re-registration. Mobility of the maxilla, for instance in the event of a LeFort I – fracture, would also preclude the use of a splint-based registration. That is, unless, of course, one considers a provisional fixation of the superior maxilla before the determination of the navigation dataset. In general, however, in such cases, the use of bone screws is certainly the simpler and better solution.

The synthetic human skull model used for the measurements is a 1:1 model of a human skull, which allowed the measurements to be comparable to those in a patient. Certainly, a smaller diameter for the measurement drillings would result in more accurate positioning of the tip of the probes, but it would not be perfectly discernible on the CBCT in all cases; thus, a drilling diameter of 1.2mm is a good compromise. In this in vitro study, the splints were placed as if on a real patient. The splint was placed before the CBCT imaging. The splint was removed before each serial measurement for referencing, and then placed again.

“Rapid” occlusal splint

The measurements based upon the “rapid” occlusal splint are sufficiently accurate for applications in practice regarding the periorbital and viscerocranial region near referencing. The “rapid” occlusal splint is very easy and quick to produce and can, therefore, be used on short-term notice during surgery. By using dataset acquisition intra-operatively, for instance via a 3D C-arm(*Terzic and Scolozzi,* 2011; *Luebbers et al.,* 2012), it is possible to make decisions intra-operatively in terms of the manufacturing of a splint, the acquisition of data, and intraoperative surgical navigation. The direct integration of the C-arm and navigation, which is not always technically possible, can thus be avoided without major problems.

Extender

The extender was manufactured from glass fiber-reinforced plastic and screwed to the splint. The reference screws were screwed onto the extender with the greatest possible distance in order to span as large a polygon as possible. However, the first measurements showed that the extender was not sufficiently rigid for registration, resulting in deviations to the landmarks of more than 8mm. Only by reinforcing the extender with two carbon fiber tubes did the intended stiffening of the design occur. The measurements in the periorbital and in the viscerocranial regions correspond to those of the “rapid” occlusal splint. In the region of the neurocranium, the advantages of referencing markers of greater distances in the extender become apparent. However, the setup of the splint with an extender is very demanding. Due to the extender and the resulting lever ratios, one must be able to place the splint very accurately and perfectly. Even the minutest deviation during the placing of the splint will result in a considerable displacement of the referencing markers and would, thus, prevent exact navigation. Another disadvantage of the extender is its considerable size. The extender can, thus, be an obstacle during surgery, depending on the operative field. Yet this problem is easy to solve if one simply removes the splint after referencing.

CONCLUSIONS

In the periorbital and the viscerocranial regions, i.e., in the direct vicinity of the registration points, measurements of errors in both splints are more or less the same with minor deviations. Only in reference to the measurements in the occipital and the temporal regions, i.e., with greater distances to the registration points, does the advantage of the extender with its reference screws of greater distances become obvious. Therefore the extender has its indication whenever it comes to surgical procedures including these specific regions.

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Last, but not least, we thank Michaela Spiess, senior librarian at the Center for Dental Medicine, University of Zurich for her support in literature full text research.

Captions

Fig. 1 – Skull model with mounted rapid splint.

Fig. 2 – Skull model with mounted extender. The 170 drilled landmarks for regional precision are numbered.

Fig. 3 – Three-dimensional view of the skull model with mounted rapid splint in the preoperative planning software (iPlan ENT 2.6; Brainlab AG, Feldkirchen, Germany). Both referencing fiducials on the splint and multiple landmarks have been digitized.

Fig. 4 – Dependency between target registration error and distance from reference marker polygon.

Fig. 5 – Target registration error mapped onto the 3D surface model. Registration via rapid splint. The error increases with distance from the reference markers.

Fig. 6 – Target registration error mapped onto the 3D surface model. Registration via extender.

	Rapid splint	Extender
Periorbital region		
Min	0.200	0.3
Max	3.000	3.8
Avg	1.500	1.760
Stdev	0.439	0.525
n	40	40
Viscerocranium		
Min	0.100	0.4
Max	4.400	4.4
Avg	1.861	1.840
Stdev	0.686	0.559
n	50	50
Neurocranium		
Min	0.400	0.2
Max	6.000	5
Avg	2.859	2.325
Stdev	0.929	0.685
n	90	90

Table 1 – Target registration error in mm for both registration techniques

REFERENCES

Alp, MS, Dujovny, M, Misra, M, Charbel, FT, Ausman, JI: Head registration techniques for image-guided surgery. Neurological research 20: 31-37, 1998.

Altobelli, DE, Kikinis, R, Mulliken, JB, Cline, H, Lorensen, W, Jolesz, F: Computer-assisted three-dimensional planning in craniofacial surgery. Plast Reconstr Surg 92: 576-585; discussion 586-577, 1993.

Bettschart, C, Kruse, A, Matthews, F, Zemann, W, Obwegeser, JA, Gratz, KW, Lubbers, HT: Point-to-point registration with mandibulo-maxillary splint in open and closed jaw position. Evaluation of registration accuracy for computer-aided surgery of the mandible. J Craniomaxillofac Surg 2011.

Eggers, G, Muhling, J, Marmulla, R: Image-to-patient registration techniques in head surgery. Int J Oral Maxillofac Surg 35: 1081-1095, 2006.

Gellrich, NC, Schramm, A, Hammer, B, Rojas, S, Cufi, D, Lagreze, W, Schmelzeisen, R: Computer-assisted secondary reconstruction of unilateral posttraumatic orbital deformity. Plast Reconstr Surg 110: 1417-1429, 2002.

Grevers, G, Leunig, A, Klemens, A, Hagedorn, H: CAS of the paranasal sinuses--technology and clinical experience with the Vector-Vision-Compact-System in 102 patients. Laryngorhinootologie 81: 476-483, 2002.

Hardy, SM, Melroy, C, White, DR, Dubin, M, Senior, B: A comparison of computer-aided surgery registration methods for endoscopic sinus surgery. Am J Rhinol 20: 48-52, 2006.

Hassfeld, S, Muhling, J, Zoller, J: Intraoperative navigation in oral and maxillofacial surgery. Int J Oral Maxillofac Surg 24: 111-119, 1995.

Hassfeld, S, Muhling, J: Navigation in maxillofacial and craniofacial surgery. Comput Aided Surg 3: 183-187, 1998.

Hassfeld, S, Brief, J, Krempien, R, Raczkowsky, J, Munchenberg, J, Giess, H, Meinzer, HP, Mende, U, Worn, H, Muhling, J: [Computer-assisted oral, maxillary and facial surgery]. Radiologe 40: 218-226, 2000.

Hassfeld, S, Muhling, J: Der Einsatz von Computer- und Robotertechnik in der Mund-, Kiefer- und Gesichtschirurgie. Zahnärztliche Mitteilungen 2: 58-66, 2000.

Hoffmann, J, Westendorff, C, Leitner, C, Bartz, D, Reinert, S: Validation of 3D-laser surface registration for image-guided cranio-maxillofacial surgery. J Craniomaxillofac Surg 33: 13-18, 2005.

Hohlweg-Majert, B, Schon, R, Schmelzeisen, R, Gellrich, NC, Schramm, A: Navigational maxillofacial surgery using virtual models. World J Surg 29: 1530-1538, 2005.

Howard, MA, 3rd, Dobbs, MB, Simonson, TM, LaVelle, WE, Granner, MA: A noninvasive, reattachable skull fiducial marker system. Technical note. J Neurosurg 83: 372-376, 1995.

Lubbers, HT, Messmer, P, Gratz, KW, Ellis, RE, Matthews, F: Misjudgments at the mandibular angle: freehand versus computer-assisted screw positioning. J Craniofac Surg 21: 1012-1017, 2010.

Lubbers, HT, Jacobsen, C, Matthews, F, Gratz, KW, Kruse, A, Obwegeser, JA: Surgical navigation in craniomaxillofacial surgery: expensive toy or useful tool? A classification of different indications. J Oral Maxillofac Surg 69: 300-308, 2011a.

Lubbers, HT, Kruse, A, Messmer, P, Gratz, KW, Obwegeser, JA, Matthews, F: Precise screw positioning at the mandibular angle: computer assisted versus template coded. J Craniofac Surg 22: 620-624, 2011b.

Lubbers, HT, Matthews, F, Zemann, W, Gratz, KW, Obwegeser, JA, Bredell, M: Registration for computer-navigated surgery in edentulous patients: a problem-based decision concept. J Craniomaxillofac Surg 39: 453-458, 2011c.

Luebbers, HT, Messmer, P, Obwegeser, JA, Zwahlen, RA, Kikinis, R, Graetz, KW, Matthews, F: Comparison of different registration methods for surgical navigation in cranio-maxillofacial surgery. J Craniomaxillofac Surg 36: 109-116, 2008.

Luebbers, HT, Zemann, W, Kruse, AL, Graetz, KW: A simple technique for sterility and patient accessibility during intraoperative three-dimensional (3D) imaging. Br J Oral Maxillofac Surg 2012.

Maciunas, RJ, Galloway, RL, Jr., Latimer, JW: The application accuracy of stereotactic frames. Neurosurgery 35: 682-694; discussion 694-685, 1994.

Marmulla, R, Niederdellmann, H: Computer-assisted bone segment navigation. J Craniomaxillofac Surg 26: 347-359, 1998.

Marmulla, R: [New possibilities of temporomandibular joint registration during orthodontic operations]. Mund Kiefer Gesichtschir 3: 67-72, 1999.

Marmulla, R, Luth, T, Muhling, J, Hassfeld, S: Markerless laser registration in image-guided oral and maxillofacial surgery. J Oral Maxillofac Surg 62: 845-851, 2004a.

Marmulla, R, Muhling, J, Wirtz, CR, Hassfeld, S: High-resolution laser surface scanning for patient registration in cranial computer-assisted surgery. Minim Invasive Neurosurg 47: 72-78, 2004b.

Marmulla, R, Eggers, G, Muhling, J: Laser surface registration for lateral skull base surgery. Minim Invasive Neurosurg 48: 181-185, 2005a.

Marmulla, R, Muhling, J, Eggers, G, Hassfeld, S: [Markerless patient registration. A new technique for image-guided surgery of the lateral base of the skull]. HNO 53: 148-154, 2005b.

Ritter, L, Yeshwant, K, Seldin, EB, Kaban, LB, Gateno, J, Keeve, E, Kikinis, R, Troulis, MJ: Range of curvilinear distraction devices required for treatment of mandibular deformities. J Oral Maxillofac Surg 64: 259-264, 2006.

Schlaier, J, Warnat, J, Brawanski, A: Registration accuracy and practicability of laser-directed surface matching. Comput Aided Surg 7: 284-290, 2002.

Schmelzeisen, R, Gellrich, NC, Schramm, A, Schon, R, Otten, JE: Navigation-guided resection of temporomandibular joint ankylosis promotes safety in skull base surgery. J Oral Maxillofac Surg 60: 1275-1283, 2002.

Schmelzeisen, R, Gellrich, NC, Schoen, R, Gutwald, R, Zizelmann, C, Schramm, A: Navigation-aided reconstruction of medial orbital wall and floor contour in cranio-maxillofacial reconstruction. Injury 35: 955-962, 2004.

Schramm, A, Gellrich, NC, Naumann, S, Buhner, U, Schon, R, Schmelzeisen, R: Non-invasive referencing in computer assisted surgery. Med Biol Eng Comput 37: 644-645, 1999.

Schramm, A, Gellrich, N-C, Nilius, M, Schon, R, Schimming, R, Schmelzeisen, R (2001). Intraoperative accuracy of non-invasive registration in computer assisted craniomaxillo-facial surgery. CARS ,Computer Assisted Radiology and Surgery, Berlin, Elsevier.

Sinikovic, B, Kramer, FJ, Swennen, G, Lubbers, HT, Dempf, R: Reconstruction of orbital wall defects with calcium phosphate cement: clinical and histological findings in a sheep model. Int J Oral Maxillofac Surg 36: 54-61, 2007.

Sun, Y, Luebbers, H-T, Agbaje, JO, Schepers, S, Vrielinck, L, Lambrichts, I, Politis, C: Validation of anatomical-landmarks based registration for image-guided surgery: An in-vitro study. J Craniomaxillofac Surg 2012.

Swennen, GRJ, Schutyser, F, Hausamen, J-E (2006). Three-Dimensional Cephalometry. A Color Atlas and Manual. Berlin Heidelberg New York, Springer.

Terzic, A, Scolozzi, P: Image guided surgical navigation integrating "mirroring" computational planning based on intra-operative cone-beam CT imaging: a promising new approach for management of primary bilateral midfacial fractures. Comput Aided Surg 16: 170-180, 2011.

Troitzsch, D, Hoffmann, J, Dammann, F, Bartz, D, Reinert, S: [Registration using three-dimensional laser surface scanning for navigation in oral and craniomaxillofacial surgery]. Zentralbl Chir 128: 551-556, 2003.

van den Elsen, PA, Pol, E-JD, Viergever, MA: Medical Image Matching - A Review with Classification. IEEE engineering in medicine and biology magazine : the quarterly magazine of the Engineering in Medicine & Biology Society 1: 26-39, 1982.

Yeshwant, K, Seldin, EB, Gateno, J, Everett, P, White, CL, Kikinis, R, Kaban, LB, Troulis, MJ: Analysis of skeletal movements in mandibular distraction osteogenesis. J Oral Maxillofac Surg 63: 335-340, 2005a.

Yeshwant, KC, Seldin, EB, Kikinis, R, Kaban, LB: A computer-assisted approach to planning multidimensional distraction osteogenesis. Atlas Oral Maxillofac Surg Clin North Am 13: 1-12, 2005b.


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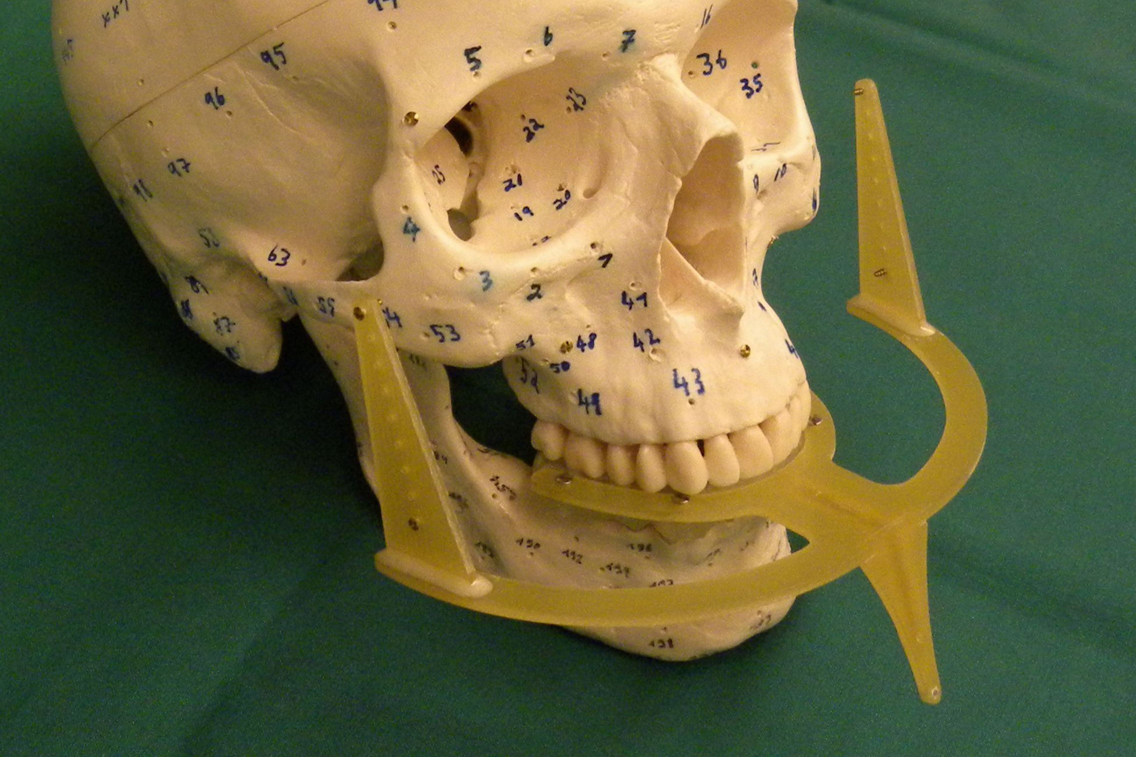
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CT #1 (Axial)
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CT #1 (Axial)
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CT #1 (Axial)
Coronal
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Functions
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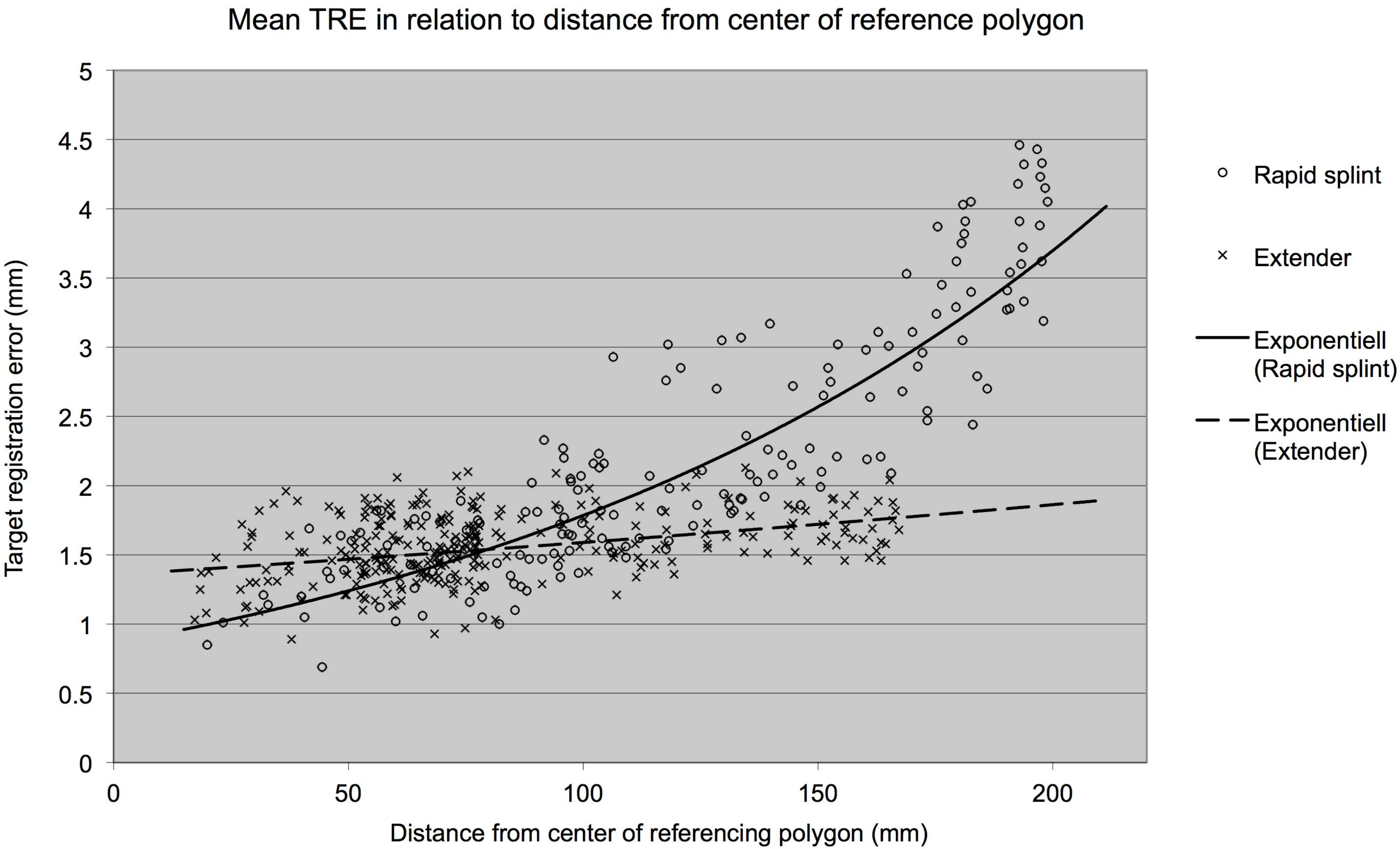
Mean TRE in relation to distance from center of reference polygon
Target registration error (mm)
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4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
50
100
150
200
Distance from center of referencing polygon (mm)
Rapid splint
Extender
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Exponentiell (Extender)